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A study on the effect of synchronization by an angle modulated signal in a single loop optoelectronic oscillator

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ABSTRACT

The present paper, aside considering the influence of a forcing signal, discusses the effect of frequency modulated synchronizing signal on optoelectronic oscillator and the corresponding FM–AM conversion for the injection synchronized optoelectronic oscillator is studied. A method to calculate the locking range of a synchronized angle modulated OEO is presented. The amplitude and phase equations are derived using the cyclic passage theory utilizing Barkhausen's criteria. The variation of modulation index and locking range with fiber delay has been presented. Finally, the growth of oscillation amplitude and the phase-plane plot of the system are studied. It is to be noted that nothing has been reported on the synchronizing capability of the angle modulated OEO as far as the knowledge of the authors goes.

1. Introduction

As the demand for high speed signal processing increases, methods utilizing photonics have gain popularity to address this need. High speed signal processing is a broader and general term that incorporates techniques and technologies to address applications covering from analog RF systems such as radars and medical ultrasound imaging to digital systems covering all the way from long haul communication networks to on-chip interconnects in computers. Photonic signal processing has been shown to address the needs of these systems due to the large instantaneous bandwidth (>40 GHz), low loss $\left(0.2\,\text{dB/km in optical fiber}\right)$ and immunity to electromagnetic interference. One of the common signal processing requirements these varied applications share is the need for very precise timing with a very low phase noise clock.

Notwithstanding the above applications, typically in RF communication, broadcasting and receiving systems, RF oscillators play an integral part. Their functions include generating, tracking, cleaning, amplifying and distributing RF carriers. Photonic RF systems [1,2] embed photonic technology into the traditional RF systems. Here, optical waves are used as a carrier to transport RF signals through optical

fiber to remote locations.

Traditional RF oscillators cannot meet all the requirements of photonic RF systems. Because photonic RF systems involve RF signals in both optical and electrical domains, an ideal oscillator for the photonic systems should be able to generate RF signals in both optical and electrical domains. In addition, it should be possible to synchronize or control the oscillator by both electrical and optical signals.

Presently, optical generation of RF signal is usually done by modulating a diode laser or an external electro-optical (E/O) modulator using a high-frequency stable electrical signal from a local oscillator (LO). But the resulting system becomes bulky, complicated, inefficient and costly. An alternate way is the beating two lasers or the techniques of sideband locking of two commercial laser diodes with the help of injection locking or optical phase locking and then heterodyning. With the help of an elaborate arrangement of these types of systems, it is not possible to realize a very narrow linewidth microwave source.

In order to fulfill all these criteria, a new type of oscillator called optoelectronic oscillator (OEO) was first proposed by Yao and Maleki [3–5] in 1996. The OEO is similar to the optoelectronic feedback circuits demonstrated by Neyer and Voges [6] in 1982, Nakazawa et al. [7] in 1984, and later by Lewis [8] in 1992. Incidentally an OEO owes its origin to the delay-line oscillators of seventies. OEO bears functional similarities with those of Berkhausen's oscillator [9,12] in the sense that, here in OEO; photons injected

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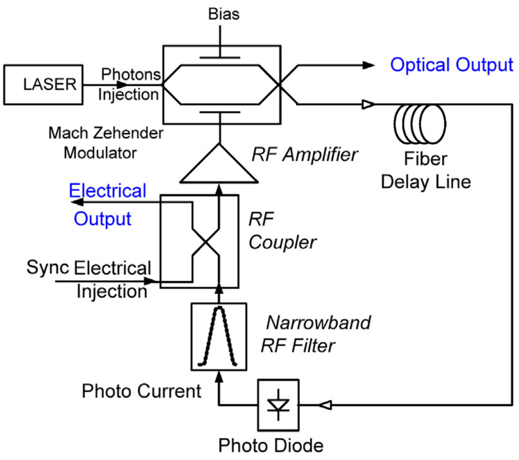

Fig. 1. Optoelectronic oscillator with FM.

from the laser are replacing the functions of electrons emitted from the cathode in an electronic oscillator (e.g. Barkhausen oscillator). But it has a structural difference from an electronic oscillator incorporating only electric circuit elements, whereas an OEO incorporates both electrical and optical circuit elements. As a result, it achieves the capability of generating high frequency signal with very low phase noise both in the electrical and optical domain.

The structure of the OEO is described in Fig. 1. Here, light from an E/O modulator is detected by a photo detector after passing through a long optical delay line which is then amplified and fed back to the electrical port of the E/O modulator. If the modulator is properly biased and the small signal loop gain is larger than unity, self-sustained oscillations are achieved. It is to be noted that the forcing signal can be injected into the OEO as an electrical or optical synchronizing signal. However, for the present study, we have considered the forcing sync signal to be in the electrical form.

In contradistinction to the previous works [3–8,14,15], this paper achieves the following: (i) system equation of the single loop optoelectronic oscillator under the influence of angle modulated synchronization has been derived, (ii) the locking range of the OEO has been evaluated and (iii) the FM–AM conversion of the synchronized OEO has been reported.

2. Theoretical description

Let us assume the input to the modulating grid of the MZM to be $v_{in}(t) = V(t)e^{j[\omega_1 t + \theta(t)]}$, and the sync signal to be $S(t) = Ee^{j[\omega_1 t + \psi(t)]}$, where '$\psi(t)$' is the input phase modulation applied to the OEO and has the form $\psi(t) = K_p \sin(\omega_m t)$; '$K_p$' being the phase deviation constant. Moreover, we assume the instantaneous phase of the OEO to be $\varphi(t) = \psi(t) - \theta(t)$, $\Delta\omega = \omega_1 - \omega_0$; '$\omega_0$' is the free-running frequency of the OEO. Let us also assume that the output of the OEO can be represented by $v_0(t) = V_0 \sin[\omega_1 t - \varphi(t)]$.

The output power of the MZM can be expressed as [11]

$$P(t) = \frac{1}{2}\alpha P_0 \left[1 - \eta \sin \pi \left(\frac{v_{in}(t) + V_B}{V_\pi}\right)\right];$$

where 'α' is the fraction of insertion loss of the modulator, 'V_π' is the half-wave voltage, 'V_B' is the bias voltage, 'P_0' is the input optical power, '$v_{in}(t)$' is the input RF voltage to the modulator and 'η' determines the extinction ratio of the modulator. Therefore, the output voltage of the photo detector when the output of the MZ modulator shines on it is $V_0(t) = \rho RP(t - \tau)$; where '$\rho$' is the sensitivity and 'R' is the output impedance of the photo-detector. Hence using the above arguments, it is not difficult to show that

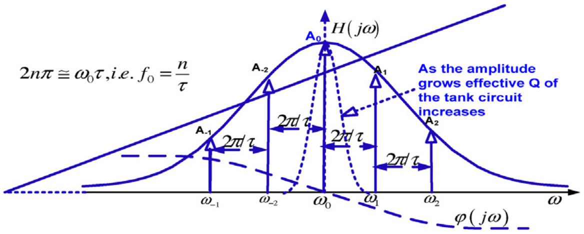

Fig. 2. Growth of oscillation in an OEO.

$$\begin{aligned} V_0(t) = V_{ph} \Bigg[& 1 - \eta \sin\left(\frac{\pi V_B}{V_\pi}\right) \left\{ J_0\left(\frac{\pi V(t-\tau)}{V_\pi}\right) \right. \\ & \left. + 2\sum_{m=1}^{\infty} J_{2m}\left(\frac{\pi V(t-\tau)}{V_\pi}\right) \cos[2m\omega(t-\tau)] \right\} \\ & - 2\eta \cos\left(\frac{\pi V_B}{V_\pi}\right) \times 2\sum_{m=0}^{\infty} J_{2m+1}\left(\frac{\pi V(t-\tau)}{V_\pi}\right) \\ & \times \sin[(2m+1)\omega(t-\tau)] \Bigg]; \end{aligned}$$

where $V_{ph} = \alpha R\rho P_0/2$. Now, if all the frequency components ($k\omega$, when k runs through 1 to N) satisfy the phase relations '$2k\pi$' and also the requisite gain of the loop exists at these frequencies, it is possible that all the 'k' modes can be excited in this system. As an example, if the optical delay is 20 μs, then the separation of these modes will be $1/\tau = 50$ kHz and if the center frequency of the RF filter is 3.0 GHz with a bandwidth of 20 MHz, then there will be 20 MHz/50 kHz = 400 modes of possible oscillations.

To justify the number of actual modes in the loop, it is to be noted that the OEO is a regenerative circuit and it incorporates a limiter type non-linear element. Moreover, it is known that the highest component of the spectrum attenuates out the smaller components and only the highest component is sustained in the loop as is evident from Fig. 2. Again, with the growth of oscillation amplitude, the effective quality factor (Q) of the tuned RF circuit becomes narrower and automatically rejects the other modes. Thus the output of the MZ modulator is seen to be

$$\begin{aligned} V_0(t) &= -2\eta V_{ph} \cos\left(\frac{\pi V_B}{V_\pi}\right) J_1\left(\frac{\pi V(t-\tau)}{V_\pi}\right) \sin[\omega(t-\tau)] \\ &= \frac{N(V(t-\tau))}{V(t)} \exp(-s\tau) v_{in}(t); \end{aligned}$$

where

$$N(V(t-\tau)) = -2\eta V_{ph} \cos\left(\frac{\pi V_B}{V_\pi}\right) J_1\left(\frac{\pi V(t-\tau)}{V_\pi}\right)$$

Moreover, it is to be noted that the total phase delay of the OEO circuit comprising of the tuned RF circuit and the optical delay line is $\phi = -(\omega - \omega_0)\tau_{cct} - \omega\tau_{fiber}$. As a result of this, within the passband of the oscillatory system, the change in 'ϕ' reaches considerable value exceeding several complete turns (2π). It is needless to mention that the effect of fiber delay will be more pronounced when one takes fiber delay in the order of nanoseconds and the form of Eqs. (4) and (6) are valid; otherwise these equations have to be modified accordingly. From now on and in the subsequent discussions to follow, 'τ_{fiber}' will be replaced by 'τ'.